A HIGH Q, LARGE TUNING RANGE, TUNABLE CAPACITOR FOR RF APPLICATIONS

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ABSTRACT

Using a new, double-sided adhesive process, an analog tunable capacitor has been designed and fabricated with an extremely large tuning range and a high Q. New design components such as two-sided metal deposition, low resistivity silicon, thicker device layers, and double beam suspensions have improved RF performance drastically. In the 200-400 MHz range that this device is intended for, Q values are in excess of 100. In addition, an 8.4 to 1 tuning ratio has been achieved with continuous tuning over a 1.4 to 11.9 pf range. To further improve dynamic performance, devices were operated in a high viscosity gas environment and near critical damping was achieved.

INTRODUCTION

MEMS technology offers an attractive capability for RF systems, particularly in support of switching and tuning functions. One such component is a micro-mechanical analog tunable capacitor, which can enable wide tuning ranges and high quality factors (Q). Existing solid state varactors typically have small tuning ratios, high resistive losses, and low self-resonance. Recent advances in micro-mechanical tunable capacitors have shown promise in improving these characteristics [1-5]. Previous MEMS tunable capacitors have shown Q values up to 290 at 1 GHz [2], tuning ratios in excess of 270% [3], and a self-resonance as high as 10 GHz [4].

In this paper we will present recent advances in an area tuning capacitor fabricated in an adhesive bonding process. This device consists of a thick, single crystal silicon device layer suspended over a glass substrate (Fig. 1). In-plane motion is achieved using a comb drive electrostatic actuator. The capacitance is tuned by adjusting the overlap of a separate interdigitated "finger" capacitor. Using new design features, tuning ratios over 740% have been achieved, while still maintaining a Q above 100 over frequencies from 200 to 400 MHz, the range that this device has been designed for. In addition, a Q as large as 36 has been achieved at frequencies up to 2 GHz.

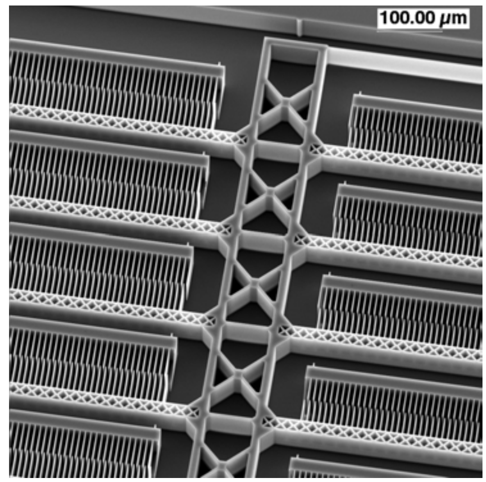

Figure 1. SEM of a 40μm thick tunable capacitor.

DESIGN AND FABRICATION

A silicon on insulator (SOI) device layer is epoxy bonded to a glass or silicon substrate as described in [5]. This process has been modified to allow for device improvements. Using a new double-sided process, metal layers can be patterned on both sides of the silicon device layer to reduce the out-of-plane bending caused by CTE mismatches between the silicon and metal layers. Prior to bonding, aluminum is patterned on the bottom side of the silicon device layer. Using a through device layer etch of alignment marks, a 0.5 μm alignment tolerance can be achieved between the top and bottom metal pattern.

Figure 2 illustrates the process sequence. The device layer of the SOI has alignment marks etched, and 2μm aluminum is deposited by evaporation and patterned by reactive ion etch using chlorine chemistry (Fig 2a). The SOI is epoxy bonded to a carrier wafer (Fig 2b). The handle wafer side and buried oxide are removed, and 2μm of metal is deposited on the topside of the device layer (Fig 2c). The aluminum and silicon are patterned with the same mask, the silicon being etched by Inductively Coupled Plasma using the Bosch process (Fig 2d). The structure is then released by isotropically etching the epoxy in an oxygen plasma (Fig 2e). After the device has been released, additional metal can be sputtered onto the structure to increase device Q. With additional metal deposited onto the top and sidewalls of the device, shorting can become an issue. Parylene deposited conformally onto the structure reduces the likelihood of shorting across a gap that is sub-micron.

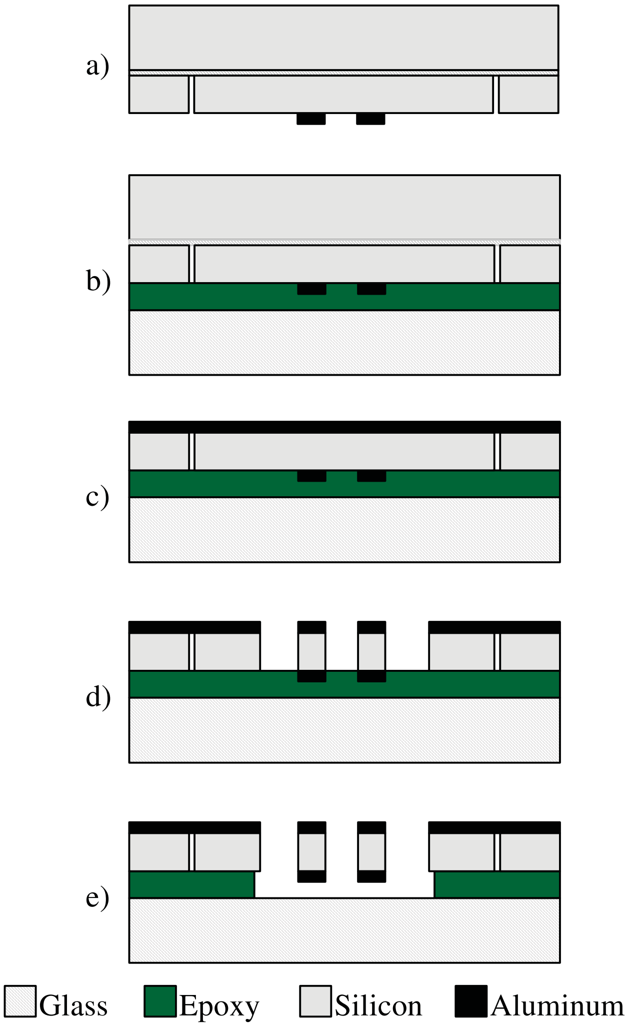

Figure 2. Schematic of the double-sided epoxy bonded process.

Multiple device design changes have improved the performance of the tunable capacitor. The width of the device suspensions has been increased for improved series resistance and decreased sensitivity to vibration. However, to still achieve the 30 µm displacement needed to tune the capacitor, a new double beam suspension has been designed (Fig. 3). Additional modifications include the use of a low resistivity (0.005-0.02 Ω*cm) device layer, and a thicker device layer. The previous process used only a 20 µm device layer. The thickest device layer attempted to date has been 80µm. The deep silicon etch has not been optimized for an 80µm device layer, however, and had a large amount of undercutting. A typical etch of a 40µm device layer is shown in Figure 4. A 1.5 µm comb finger can be etched into a 40 µm device layer with extremely straight sidewalls with only limited undercutting.

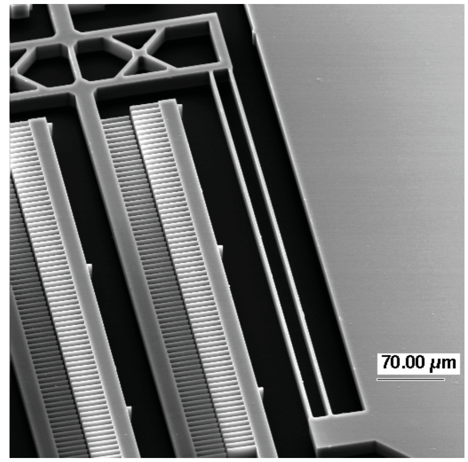

Figure 3. SEM of a new double beam suspension that allows wider suspensions to still achieve large displacements.

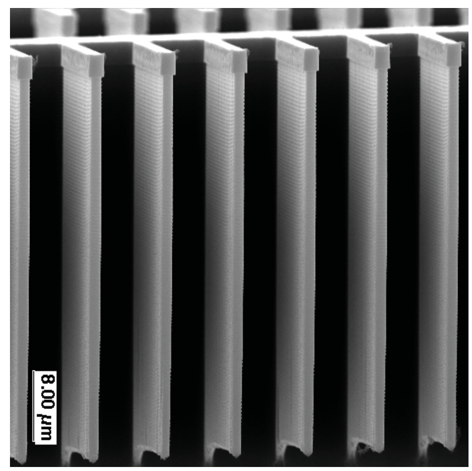

Figure 4. SEM of 1.5 µm comb fingers etched into a 40 µm device layer.

RESULTS

The two-sided metalization successfully counterbalanced the mismatched stress, reducing the out-of-plane bending from 4.5µm to 0.2 µm. These measurements were made on a white light interferometer. This reduction in device bow not only allows full engagement of the comb fingers, but also allows thick metal layers to be deposited without performance problems. The device is designed with ground-signal-ground probe pads, with 150µm spacing. An HP8753D network analyzer, using probe tips with the same pitch distance and calibrated with open, short, and load, was used to measure the capacitance and S parameters.

The use of the 40 µm device layer achieved an exceptionally large tuning range, larger than 8.4 to 1 (Fig 5). Although theoretically the device layer thickness should not affect the tuning range, the ratio of parasitic capacitance to the base capacitance of the device is greatly improved with a thicker device layer. This effect has allowed the tuning ratio to be greatly increased.

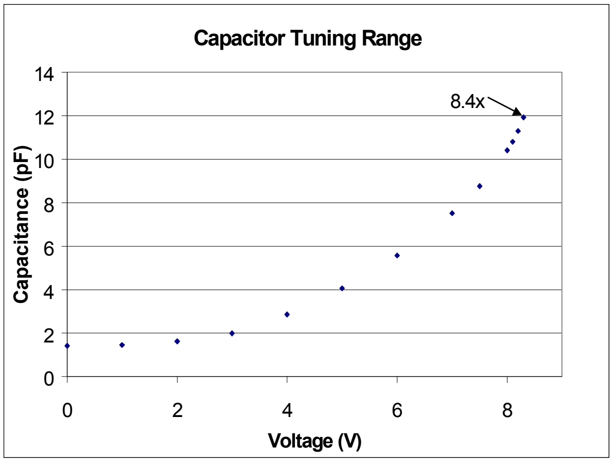

Figure 5. Tuning range of the device measured at 500 MHz.

The thicker two-sided metal, the low resistivity silicon device layer, and the wider suspension designs have reduced the series resistance to less than 1 Ω. This lower resistance has increased the device Q. Figures 6 and 7 show the S11 parameters and the device Q at the minimum capacitance. The device has a low parasitic effect and is not near self-resonance out to a frequency of 3 GHz. The device also has a Q above 100 out to 700 MHz, making it ideal for the tunable filter application in the 200 – 400 MHz range that the device was designed for. In addition, the device has a Q above 30 up to 2.25 GHz making it suitable for higher frequency applications.

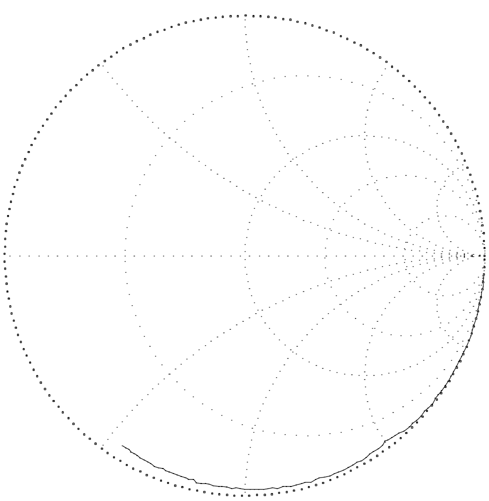

Figure 6. S11 plot of the device from 100 MHz to 3 GHz with no actuation and a capacitance of 1.5 pf.

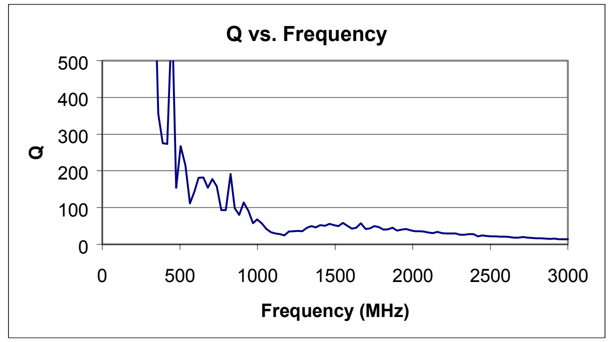

Figure 7. Quality factor of the device from 300 MHz to 3 GHz with no actuation and a capacitance of 1.5 pf.

Figures 8 and 9 show the S11 parameters and the device Q at the maximum capacitance. The increased capacitance reduces the self-resonance down to around 2 GHz. In addition, the Q factor is reduced, but remains above 100 up to 200 MHz, the intended operation frequency at the 8 pf capacitance range.

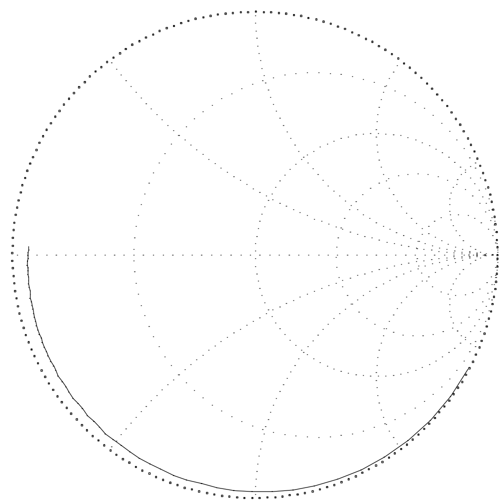

Figure 8. S11 plot of the device from 100 MHz to 2 GHz with an actuation voltage of 7 V and an 8 pf capacitance at 200 MHz.

For better series resistance, stiffer devices, and improved device linearity over 30µm displacements, spring designs were made wider and longer. Adjusting the design from a 2 µm wide suspension to a double 3 µm wide suspension reduced the series resistance by 30%. The longer spring devices have shown less twisting and therefore no comb finger rubbing and sticking when the 30 µm fingers are fully engaged. The resonant frequency was also increased 25% by reducing the mass of the device by hollowing out the capacitor arms.

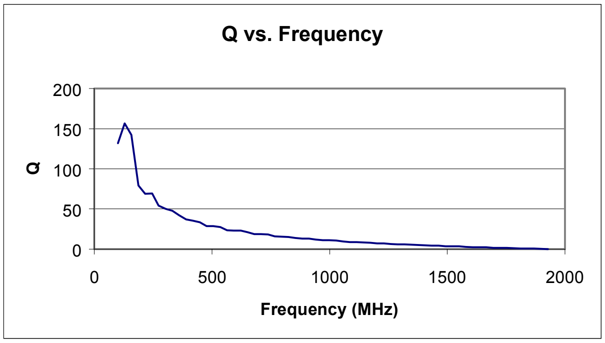

Figure 9. Quality factor of the device from 100 MHz to 2 GHz with an actuation voltage of 7 V and a capacitance of 8 pf at 200 MHz.

In addition to increasing the device stiffness for improved response time and vibration isolation, the comb drive structure was analyzed in viscous inert gases. This revealed that devices packaged in a neon environment could be near critically damped, and would therefore be easier to control and have faster response times. Figure 10 shows the mechanical resonance measured for the same device in different ambient gasses. The step response for another device shows near critical damping in a neon environment (Fig. 11). This measurement was made using a commercially available capacitive sensing ASIC.

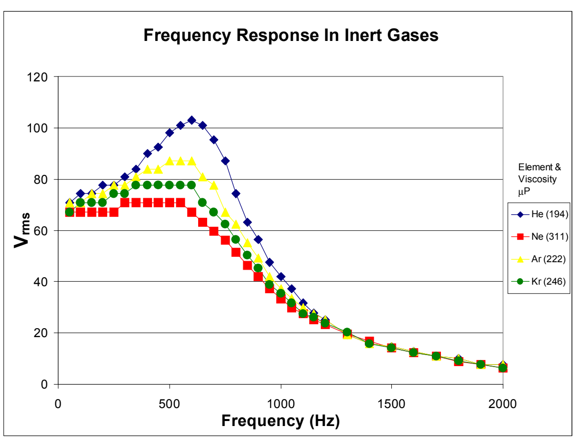

Figure 10. Frequency response of comb drive devices of comparable structure in different ambient gasses.

CONCLUSIONS

A micro-mechanical tunable capacitor was designed and fabricated for implementation into a 200 to 400 MHz tunable filter circuit. Using new design and process concepts, a 740% continuous tuning range has been achieved with Q factors above 100 for the operating conditions of the tunable filter. The dynamic performance of the device was also improved by operating in a high viscosity gas environment and by using a reduced mass

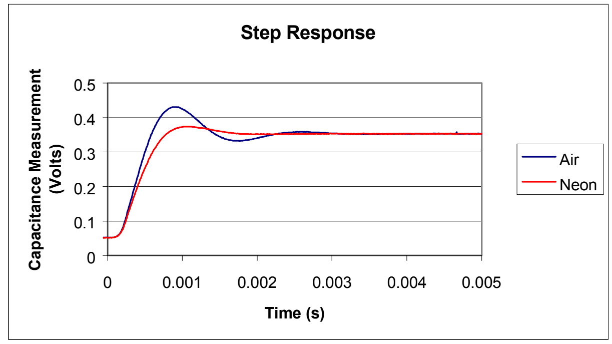

Figure 11. Step response of a device showing near critical damping in a neon environment.

device design. In addition, adaptation into higher frequency ranges has been proven feasible with Q factors over 35 for frequencies up to 2 GHz. Trading off the tuning range for higher Q by stiffening up the device suspension could also make additional gains.

ACKNOWLEDGMENTS

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